Exploitation of Environmental Complexity in Shallow Water Acoustic Data Communications

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LONG-TERM GOALS

Conduct feasibility experiments and associated algorithm design to explore how complexity of the shallow water acoustic environment can be used advantageously in acoustic data communications.

OBJECTIVES

Exploit environmental complexity through both real and synthetic aperture spatial processing to mitigate multipath-related fading and intersymbol interference in acoustic data communications.

APPROACH

The origin of this research is our experience with carrying out ocean acoustic time reversal experiments over a broad range of frequencies. Through a series of experiments conducted jointly between MPL and the NATO Undersea Research Centre (NURC), we have demonstrated that complexity of the ocean environment fundamentally is advantageous and facilitates rather than inhibits the resolution of physical processes, detection of targets, and acoustic telemetry of data. Furthermore, the time reversal experiments have illustrated that the ocean maintains a far greater inherent coherence than previously has been thought possible. Thus, the overall goal of this research is to take advantage of the self-adaptive nature of the complex ocean environment and learn how to exploit fluctuations, scattering, and variability.

Multiple-Input / Multiple-Output (MIMO) Acoustic Data Communications

The active time-reversal approach directly achieves spatial diversity through use of an array of sources. Source array diversity can be complemented with receive array diversity to enable transmitting independent communication sequences in parallel thus increasing the total data rate through the channel. The source array and receive array pair implements a multiple-input/multiple-output (MIMO) system. Although not optimized for overall communication system performance, the time-reversal approach is straightforward, results in relatively compact two-way channel responses, and yields high SNR at the focal depths of the communication sequences. Furthermore, the simple strategy of post-processing the communication sequence observed at a focal depth with a single-channel equalizer can prove effective.

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Synthetic Aperture Acoustic Data Communications

Here our objective is to exploit the dynamic propagation complexity arising from source-receiver motion to achieve the equivalent of an extended physical aperture with a single source-receiver pair. The underlying approach involves using distributed aperture time reversal to compensate for channel dispersion and the resulting problem of intersymbol interference (ISI). In order to fully understand medium complexity in the role of enhancing construction of the synthetic aperture, the focal region structure and temporal sidelobe characteristics obtained with a synthetic aperture array in the ocean medium needs to be explored. In addition, since we typically record transmissions on a vertical receive array, a direct comparison can be made between the synthetic aperture approach to a single receive array element and passive time reversal where a single transmission is received on multiple receive array elements – as well as combinations of the two. Essentially, we will be investigating how the medium complexity maps into spatial diversity between the source and receive array.

WORK COMPLETED

Experimental data collected during a joint experiment with the NATO Undersea Research Centre (NURC) in 2004 has been used to demonstrate an iterative equalization and decoding approach for acoustic communication [5]. Data transmission was demonstrated in 120 m deep water between a fixed source 110 m deep and the individual hydrophones of a 32-element vertical receiving array at a range of 10 km.

RESULTS

In passive time reversal, the channel response $h_i^j(t)$ from each source (or user) (superscript j) to each receiver element (subscript i) is obtained from a channel probing waveform prepended to each data packet (e.g. a LFM chirp). Matched filtering then is applied at every receiver element with $h_i^j(-t)$ and these results are combined coherently across the M receiving elements for a given user [1-3]. Complexity of the channel is beneficial for time reversal communications yielding an aggregate response for each user after multichannel combining close to a delta function (expressed analytically as the summation of the autocorrelations of each channel impulse response and denoted by q(t) in [1-2]). After multichannel combining, each user signal is processed with a single channel decision feedback equalizer (DFE) to remove any residual intersymbol interference (ISI) and compensate for channel fluctuations during the packet transmission. This same approach can be applied in a synthetic aperture context where multiple transmissions (separated spatially) substitute for multiple receive elements [4].

As an alternative to the passive time reversal technique described above, an iterative equalization and decoding approach has been developed for recovering information transmitted through a shallow water communication channel [5]. The procedure has three main tasks: estimation of channel model parameters (CMPs), channel equalization, and decoding. These tasks are performed cyclically until the algorithm converges. Information bits are convolutionally encoded, punctured and permuted, mapped into QPSK symbols, linearly modulated, and transmitted. Training symbols are prepended to the transmitted sequence for initial estimation of the CMPs. The algorithm processes data from a single receive sensor.

Data received on a vertical array was processed and the performance of the algorithm for each sensor in the array evaluated. The data was collected during a July 2004 experiment with NURC in a shallow water region north of Elba Island, Italy. The sound speed structure and experimental geometry are shown in Fig. 1.

There is negligible Doppler spread in the received data. However, difference between transmitter and receiver clocks as well as slight motion of the receive array produces a nonnegligible compression of the received signals. Consequently, there is an observable Doppler “shift.” Nonuniform resampling of the data produces time series modeled as the output of a linear time-invariant system. Resampling and CMP estimation are done iteratively, in conjunction with equalization and decoding. Fig. 2 illustrates the SNR measured across the array, the channel impulse response (CIR) estimates for three of the array elements, and their respective sampling time offsets.

Fig. 3 illustrates the iterative process. It shows the linear equalizer (LE) output scatter plots for the first three iterations using data from Sensor 24. Successive improvement of the equalization step of the processing is demonstrated via an increase in LE output SINR from 2.1 to 8.0 dB. A further example showing the improvement in bit errors with iteration is shown in Fig. 4. Here the results are shown in tabular form for 7 of the array elements. The algorithm successfully processes the data to yield few or no information bit errors.

IMPACT / APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA and NRL which are exploring various aspects of high frequency channel characterization with specific applications to acoustic data communications and includes experimental work with the NATO Undersea Research Centre (NURC) and the recent KauaiEx (2003) and Makai (2005) experiments.

PUBLICATIONS

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[4] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, T. Akal, and M. Stevenson, "High-rate synthetic aperture communications in shallow water," IEEE J. Oceanic Eng. (submitted, 2008).

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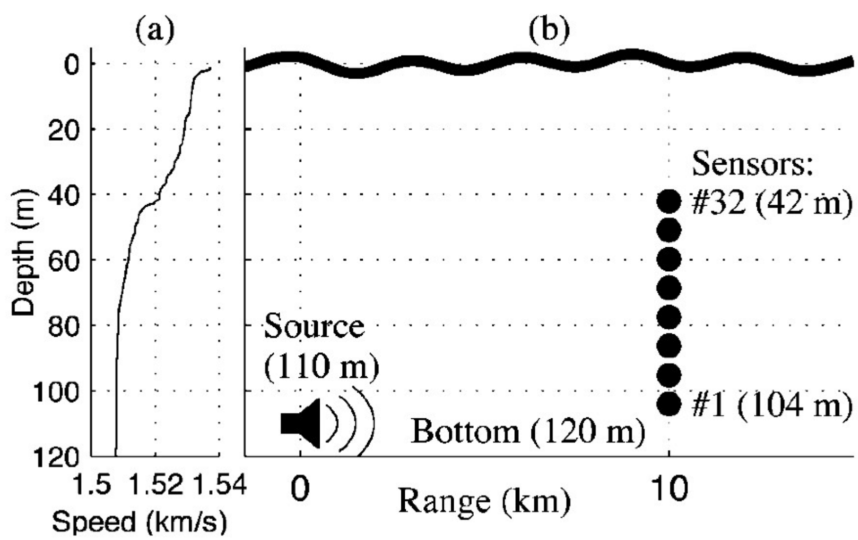

Figure 1. (1) Measured downward-refracting sound speed profile. (b) Shallow water experiment geometry north of Elba Island, Italy.

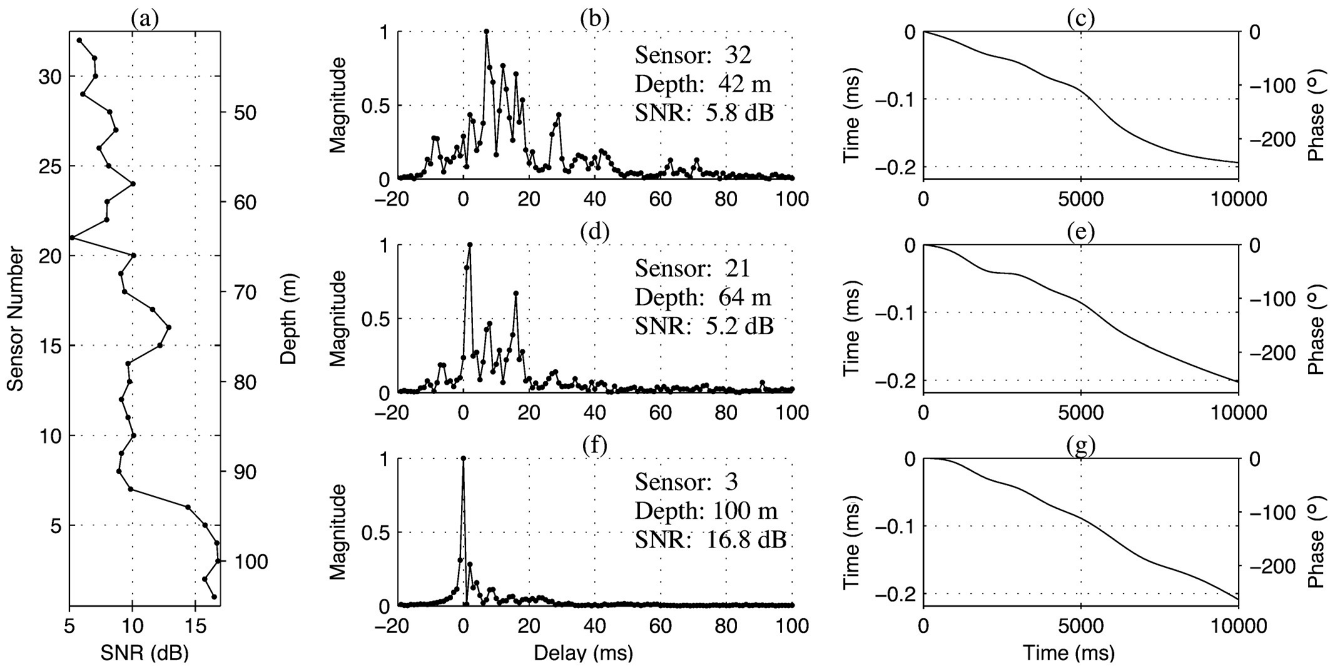

Figure 2. (a) SNR measured across entire array. Left axis is sensor number and right axis is sensor depth. (b) Channel impulse response (CIR) estimated for Sensor 32. (c) Estimated sampling time offset for Sensor 32. Right axis shows corresponding phase rotation. (d) and (e) CIR and sampling time offset for Sensor 21. (f) and (g) CIR and sampling time offset for Sensor 3.

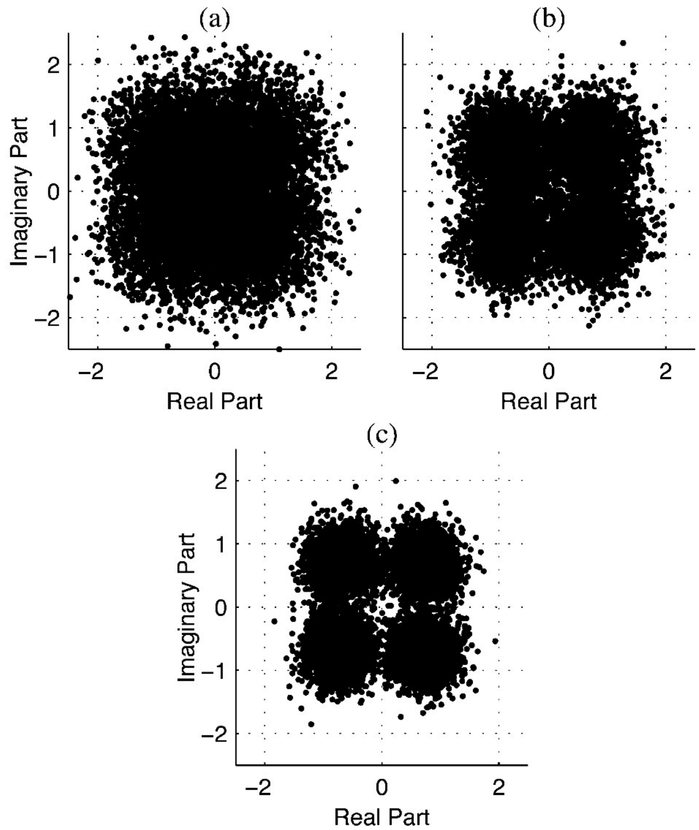

Figure 3. Scatter plots of the linear equalizer (LE) output for Sensor 24 illustrating iterative improvement in the equalization process. (a) First iteration: LE output SINR = 2.1 dB. (b) Second iteration: LE output SINR = 5.6 dB. (c) Third iteration: LE output SINR = 8.0 dB.

Sensor		21	22	26	29	30	31	32
Depth (m)		64	62	54	48	46	44	42
SNR (dB)		5.2	8.0	7.4	6.1	7.1	7.0	5.8
Iteration	1	1315	710	618	2033	1217	448	2679
	2	509	264	21	1110	281	12	2092
	3	159			494	6		1346
	4	32			155			739
	5	12			16			267
	6	5			10			81
	7	5						1
	8	5						
	9	5						
	10	5						

(Blank entries indicate zero errors)

Figure 4. Number of bit errors for the sensors with SNR below 8 dB.